

A dynamic global radio-frequency noise survey as observed by the FORTE satellite at 800-km altitude

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Abstract

We present a dynamic global radio-frequency survey of noise observed from the FORTE satellite at 800 km altitude. This is a survey of squared amplitudes in 44 sub-bands each spaced by 0.5 MHz centered at 38 MHz ("lo-band") and 44 sub-bands spaced by 0.5 MHz centered at 130 MHz ("hi-band"). More specifically, we survey the distribution of $\mathbf{R}^2 / \overline{\mathbf{R}}^2$, where R^2 is the squared amplitude at a given frequency and $\overline{\mathbf{R}}^2$ is the most recent mean squared amplitude. The definition of "most recent" ranges from 10 microseconds to 10 s. We also vary the fraction of the update period used to compute the mean from 0.1% to 100% of the period.

We define 13 geographic regions and analyze signal-free regions of event data generated from 1997 to 1999. We use cross validation to adequately sample the distribution of $\mathbf{R}^2 / \overline{\mathbf{R}}^2$ across time. Summary statistics presented include percentiles of the distribution and fractions exceeding thresholds in each of 44 frequency bands spaced by 0.5 MHz for the lo and hi frequency bands in each of the geographic regions.

1 Introduction

Space-based observations of radio frequency (RF) emissions have several applications, including lightning RF signatures and an exciting area of cosmic ray research involving an unknown source of highly energetic primary particles [Jacobson et. al. 1999]. The FORTE [Jacobson et. al. 1999] satellite records Very High Frequency (VHF) RF observations in a lo (centered at 38 MHz) and hi (centered at 130 MHz) band receiver.

RF emissions that satisfy a multi-band trigger criterion are archived and these "event records" include pre and post signal regions that remain available to evaluate. We assume that these signal-free regions provide a representative sample of the RF noise and provide an RF noise survey by evaluating these regions of the event records. We use simple thresholding to extract the signal and then analyze the two remaining signal-free regions.

A companion paper [Burr et. al., 2002a] presented a "static" survey of amplitudes at each of 44 sub-bands spaced by 0.5 MHz (from 26.5 to 48 MHz in the lo-band and from 118.5 to 140 MHz in the hi-band). This paper provides a "dynamic" survey of the distribution of $\mathbf{R}^2 / \overline{\mathbf{R}}^2$, where R^2 is the squared amplitude and $\overline{\mathbf{R}}^2$ is the most recent mean squared amplitude. The definition of "most recent" ranges from 10 microseconds to 10 s. We also vary the fraction of the update period used to compute the mean from 0.1% to 100% of the period.

Appendix A provides more detail about our spectral analysis approach. Briefly, any sequence of n numbers X_1, X_2, \dots, X_n (our input raw data is the electric field E in v/m as recorded at the satellite) has the Fourier series representation (we assume that n is even for convenience) $X_t = a_0 + \sum_{p=1}^{n/2-1} \{a_p \cos(2\pi pt/n) + b_p \sin(2\pi pt/n)\}$ which, for $p = n/2$ is equivalent to $X_t = a_0 + \sum_{p=1}^{n/2-1} \{R_p \cos(\omega_p t + \phi_p)\}$ with the phase $\phi_p = \tan^{-1}(-b_p/a_p)$. We refer to R_p as the amplitude at frequency p . Like the

electric field E , R_p is in units of v/m. In this paper we report smoothed estimates of $(R_p)^2$ using a 1 MHz wide smoother, and for graphing purposes, we usually plot $10 \times \log_{10}(\frac{R^2}{\bar{R}^2})$ (decibels, dB).

2 The FORTE Satellite

On August 29, 1997 the Fast On-Orbit Recording of Transient Events (FORTE) satellite was launched as a joint experiment between Los Alamos National Laboratory and Sandia National Laboratory. The goal has been to provide advanced RF impulse detection and characterization. FORTE was launched into a nearly circular low-earth orbit at an approximate altitude of 800 km and 70 degree inclination. The emphasis of this satellite is on the measurement of electromagnetic pulses, primarily due to lightning, within a noise environment dominated by continuous wave carriers, such as TV and FM stations [nis-www.lanl.gov/nis-projects/forte]. The FORTE payload consists of three measurement instruments: an RF system, an optical system, and an ``event classifier.'' These systems have previously been described in detail [Jacobson et. al. 1999]. For convenience we will briefly describe the RF system here.

The RF system is designed to receive, digitize, store and down-link records of interest. These records contain VHF time-series of the RF electric field, E , digitized at a rate of 50 Megasamples/second. [Jacobson, 2002]. Typically data is collected in two 22 MHz wide passband regions (lo and hi). When a multi band trigger criterion is met, typically twelve-bit data is collected from one or both of these passbands for a period of 409.6 microseconds, although event records exist with a collection period of two and four times this duration. One quarter of the collected waveform is produced from the pre-trigger, and because the events are usually very short, nearly three quarters of the waveform is from the post-trigger.

Each RF passband receiver has embedded within it eight independent triggering sub-bands spaced at 2.5 MHz with 1 MHz bandwidths. The two 22 MHz receivers are triggered together enabling both to be digitized synchronously. The trigger rule requires coincidence (within 160 microsec for the lo-band and within 10 microsec for the hi-band) of typically five (or more) of the eight sub-band triggers. Triggering is usually produced by the lo-band. Each 1 MHz trigger sub-band has a noise compensation option in which the threshold may be either set at an absolute level or as a value $10 \times \log_{10}(dB)$ above a low-pass filtered noise level in that sub-band (i.e., as a noise riding threshold). Normally the signal is required to rise 14 to 20 dB above the background noise in order to trigger a given sub-band. As we will show, noise can vary by 20 dB between the quietest and the noisiest portions of the earth.

3 Data Selection and Preprocessing

The RF receiver on the FORTE satellite has collected several hundred thousand transionospheric pulse pair (TIPP) events from November 1997 to December 1999. These TIPP events are defined as VHF signals consisting of two broadband pulses, each with a duration of a few microseconds [Tierney et. al. 2002] and a characteristic shape. TIPPs are generally associated with thunderstorms and therefore result in several recorded events in a particular earth region during a single satellite pass over that region. TIPP events typically exhibit at least a 1 ms separation. Therefore, this noise survey will rely on raw data (the electric field E in v/m) in the form of a time series of signal-free regions from each event, with gaps of 1 ms or more between event records that are each usually 409.6 microseconds in duration (a few are 819.2 or 1638.4 microseconds in duration).

As mentioned in the introduction, RF emissions that satisfy a multi-band trigger criterion are archived and these ``event records'' include pre and post signal regions that remain available to evaluate. We assume that this signal-free region provides a representative sample of the RF noise. For this survey only TIPP events collected by FORTE's RF receivers within the lo and hi frequency ranges are considered. We use thresholding to extract the very-short-in-duration signal (any value that exceeds 5 times the median value in the entire record is considered a signal) and then analyze the two remaining signal-free regions (one pre-signal region lasting approximately 100 microsec and one post-signal of region lasting approximately 300 microsec in the 409.6 microsec records).

All events are then grouped into 1 of 13 bins describing their position on the earth based on recorded latitude and longitude. If the closest ground coordinate (listed in [Table I](#)) is within 5000 km of the satellite data point the event is classified as belonging to the specified earth region. The events are further classified by regional pass where all events in a particular pass are classified as belonging to the same region and all occur within approximately a 15 minute time window. Generally, the South Atlantic region is quiet so few TIPP events are recorded there, and the satellite downlink occurs in the NE Pacific region, resulting in few TIPP events being recorded for that region.

See Appendix B for a list of the data saved for each 10 microsecond window extracted from the signal-free region of each event record.

4 The Static Noise Survey

This paper extends [Jacobson et. al., 1999] by extracting the signal-free region of each event record for each of 13 geographic regions as described in the previous section. It also extends [Burr et. al., 2002a] by experimenting with different noise update schemes. In [Burr et. al., 2002a], we computed and archived estimates of squared amplitude R^2 from each of 44 evenly spaced frequencies in 0.5 MHz steps from 26.5 to 48 MHz, and from 118.5 to 140 MHz from each full 10 microsecond time segment from each of the two signal-free time segments from each of many passes over each of 13 geographic regions.

For each geographic region we summarized the distribution of R^2 at each frequency using plots of:

- (a) an estimate of the mean of R^2 and confidence limits. In all cases, the limits are at the estimate \mp twice the standard deviation of the estimate at each frequency, including the means from several partitions;
- (b) same as (a) except it is for the median;
- (c) an estimate of 6 high percentiles of R^2 and confidence limits of the estimate at each frequency, including the estimate from each of several partitions. Percentiles were given in pairs that were chosen [Serfling, 1980] for bounding the 99th, 97th, and 95th percentiles with 99% probability;
- (d) an estimate of the fraction of $10 \times \log_{10}(R^2)$ that exceed the thresholds $T = 3, 5, 7, 10, 15, 16, 17, 18, 19$, and 20, the confidence limits at each frequency, and
- (e) an estimate of the minimum and maximum of R^2 and associated confidence limits.

Other summary information from this static noise survey is available below.

5 A Dynamic Noise Survey

The FORTE ``trigger algorithm'' includes a noise riding threshold such that the squared amplitude R^2 (in dB) in each of 8 bands is compared to the noise in that band. The sub-band ``alarms'' if $10 \times \log_{10}(\frac{R^2}{\bar{R}^2}) > T$, where T is a tunable threshold, and is typically set at approximately 18. There is a periodic ``state-of-health'' sample that is used to update \bar{R}^2 every 4 seconds.

In this section, we investigate the impact of using different ``update the mean'' rules on the allowed T for a given false alarm rate. For example, suppose we updated the \bar{R}^2 every 100 microseconds and used 1/2 the update interval (50 microseconds) to define \bar{R}^2 . If we had 5 consecutive 10 microsecond windows, this would imply that we average over 5 R^2 s to define \bar{R}^2 .

We considered 6 update intervals (UI, in seconds): $10^{-5}, 4 \times 10^{-4}, 10^{-2}, 10^{-1}, 1$, and 10 , and 4 update fractions (UF): 0.001, 0.01, 0.1, and 1. Note that an update fraction of 1 implies that we use the entire update interval to define \bar{R}^2 . At one extreme, if the update interval is 10^{-5} , then we must use an update fraction of 1 because we insist that the entire window be completed within the time $UI \times UF = 10^{-5}$, which is the size of our 10 microsecond windows. This implies that we do not observe any data with $UI = 10^{-5}$ and $UF < 1$. This leads to $6 \times 4 = 24$ possible ``update the mean'' rules, but 5 are impossible combinations with 10 microsecond windows, such as $UI = 10^{-5}$ and $UF < 1$ (See [Table II](#)).

The dynamic noise survey extends the static survey in that we search for passes within a geographic region having ``close-in-time'' waveforms. As with the static survey, we calculate R^2 at each center frequency, but we now also record the starting time of each 10 microsecond window. Suppose we have 100 close-in-time 10 microsecond windows, starting at times t_1, t_2, \dots, t_{100} . We will illustrate the update scheme with the case $UI = 10^{-1}$ and $UF = 0.1$. Begin with window 1 at time t_1 and all windows that complete within $UF \times UI = 0.01$ s of t_1 will enter into the calculation of $\overline{R^2}$. And, all windows that start at or after $t_1 + UF \times UI = t_1 + 0.01$ s and finish before $t_1 + UF \times UI + UF$ will be ``test windows'' that contribute to the summary statistics ($\overline{R^2} / \overline{\overline{R^2}}$) for that case. Move forward in time to find the next window to repeat the same process until all windows are used. We repeat this procedure for each of the $24 - 5 = 19$ possible combinations of UI and UF.

The effect of the update rule depends on the:

a) smoothing scheme;

Highly smoothed R^2 (dB) estimates are less variable so the differences among update rules are smaller. We report results here only for moderate smoothing using the 1MHz bandwidth.

b) time window,

(1-10) microseconds (100, 250, and 500 points with $\delta t = 20 \times 10^{-9}$ s. We report results only for the 10 microsecond windows.

c) and whether we compute \log_{10} of the average of R^2 or the average of $\log_{10}(R^2)$.

The average of logs tends to put more weight on small values (large negative log values) and the log of the average puts more weight on large values. Usually, the log of the average is preferred because small values are most susceptible to perturbations such as leakage from other frequencies [Bloomfield, Chapter 7]. In all cases reported here, we compute $10 \times \log_{10}$ of the average.

For the dynamic survey, we are interested in the distribution of $\overline{R^2} / \overline{\overline{R^2}}$. In Figures 1a to 1g we plot the following features of this distribution for the lo-band in the Africa region:

[Figure 1a](#) an estimate of the probability that $10 \times \log_{10}(\overline{R^2} / \overline{\overline{R^2}})$ exceeds the thresholds $T = 3, 5, 7, 10, 15, 16, 17, 18, 19$, and 20, and the confidence limits at each frequency for each of the 19 possible cases in the 6-by-4 grid;

[Figure 1b](#) same as Figure 1a except we only show the best (lowest fraction exceeding T) and worst (highest fraction exceeding T) among the 19 cases;

[Figure 1c](#) same as Figure 1b except that ``best'' and ``worst'' are defined for each threshold T rather than by using the median over all T to define best and worst;

[Figure 1d](#) comparison of the best dynamic ``update-the-mean'' rule to a static rule that uses the mean in each partition (which spans tens or hundreds of days);

[Figure 1e](#) an estimate of the probability that $10 \times \log_{10}(\overline{R^2} / \overline{\overline{R^2}})$ exceeds $T = 10$ for a 1 MHz wide sub-band centered at 31 MHz for each of the 19 ``update-the-mean'' cases and for the static case. The 6 UI values are coded 1 through 6 and the 4 UF values are displayed in the legend;

[Figure 1f](#) same as Figure 1e except for $T = 18$, and

[Figure 1g](#) an estimate of the minimum and maximum of $\overline{R^2} / \overline{\overline{R^2}}$ and associated confidence limits (displayed using the dB scale).

[Figure 1h](#), [Figure 1i](#), [Figure 1j](#), [Figure 1k](#), [Figure 1l](#), [Figure 1m](#), [Figure 1n](#) are the same, except are for the hi-band in Africa. Figures 2 to 13 are the same as Figure 1, but are for the other 12 geographic regions. Appendix C provides additional numerical summaries.

Australasia: [Figure 2a](#), [Figure 2b](#), [Figure 2c](#), [Figure 2d](#), [Figure 2e](#), [Figure 2f](#), [Figure 2g](#), [Figure 2h](#), [Figure 2i](#), [Figure 2j](#), [Figure 2k](#), [Figure 2l](#), [Figure 2m](#), [Figure 2n](#)

Central America: [Figure 3a](#), [Figure 3b](#), [Figure 3c](#), [Figure 3d](#), [Figure 3e](#), [Figure 3f](#), [Figure 3g](#), [Figure 3h](#), [Figure 3i](#), [Figure 3j](#), [Figure 3k](#), [Figure 3l](#), [Figure 3m](#), [Figure 3n](#)

Conus: [Figure 4a](#), [Figure 4b](#), [Figure 4c](#), [Figure 4d](#), [Figure 4e](#), [Figure 4f](#), [Figure 4g](#), [Figure 4h](#), [Figure 4i](#), [Figure 4j](#), [Figure 4k](#), [Figure 4l](#), [Figure 4m](#), [Figure 4n](#)

Indian Ocean: [Figure 5a](#), [Figure 5b](#), [Figure 5c](#), [Figure 5d](#), [Figure 5e](#), [Figure 5f](#), [Figure 5g](#), [Figure 5h](#), [Figure 5i](#), [Figure 5j](#), [Figure 5k](#), [Figure 5l](#), [Figure 5m](#), [Figure 5n](#)

North Atlantic: [Figure 6a](#), [Figure 6b](#), [Figure 6c](#), [Figure 6d](#), [Figure 6e](#), [Figure 6f](#), [Figure 6g](#), [Figure 6h](#), [Figure 6i](#), [Figure 6j](#), [Figure 6k](#), [Figure 6l](#), [Figure 6m](#), [Figure 6n](#)

NE Pacific: [Figure 7a](#), [Figure 7b](#), [Figure 7c](#), [Figure 7d](#), [Figure 7e](#), [Figure 7f](#), [Figure 7g](#), [Figure 7h](#), [Figure 7i](#), [Figure 7j](#), [Figure 7k](#), [Figure 7l](#), [Figure 7m](#), [Figure 7n](#)

NW Pacific: [Figure 8a](#), [Figure 8b](#), [Figure 8c](#), [Figure 8d](#), [Figure 8e](#), [Figure 8f](#), [Figure 8g](#), [Figure 8h](#), [Figure 8i](#), [Figure 8j](#), [Figure 8k](#), [Figure 8l](#), [Figure 8m](#), [Figure 8n](#)

South America: [Figure 9a](#), [Figure 9b](#), [Figure 9c](#), [Figure 9d](#), [Figure 9e](#), [Figure 9f](#), [Figure 9g](#), [Figure 9h](#), [Figure 9i](#), [Figure 9j](#), [Figure 9k](#), [Figure 9l](#), [Figure 9m](#), [Figure 9n](#)

South Atlantic: [Figure 10a](#), [Figure 10b](#), [Figure 10c](#), [Figure 10d](#), [Figure 10e](#), [Figure 10f](#), [Figure 10g](#), [Figure 10h](#), [Figure 10i](#), [Figure 10j](#), [Figure 10k](#), [Figure 10l](#), [Figure 10m](#), [Figure 10n](#)

SE Asia: [Figure 11a](#), [Figure 11b](#), [Figure 11c](#), [Figure 11d](#), [Figure 11e](#), [Figure 11f](#), [Figure 11g](#), [Figure 11h](#), [Figure 11i](#), [Figure 11j](#), [Figure 11k](#), [Figure 11l](#), [Figure 11m](#), [Figure 11n](#)

SE Pacific: [Figure 12a](#), [Figure 12b](#), [Figure 12c](#), [Figure 12d](#), [Figure 12e](#), [Figure 12f](#), [Figure 12g](#), [Figure 12h](#), [Figure 12i](#), [Figure 12j](#), [Figure 12k](#), [Figure 12l](#), [Figure 12m](#), [Figure 12n](#)

SW Pacific: [Figure 13a](#), [Figure 13b](#), [Figure 13c](#), [Figure 13d](#), [Figure 13e](#), [Figure 13f](#), [Figure 13g](#), [Figure 13h](#), [Figure 13i](#), [Figure 13j](#), [Figure 13k](#), [Figure 13l](#), [Figure 13m](#), [Figure 13n](#)

Additional tabular summary data for each case for each geographic region for the lo and hi-band for each of 50 frequencies is listed in Appendix C.

Some explanation of Figures (a)-(c) is necessary because we selected the best and worst of 19 cases, so there is a selection effect. Figures (b) and (c) are the same as (a) except that it only plots the best and worst cases (best and worst are defined by using the median probability over all frequencies). For many frequencies, the gap between best and worst appears to be real because the error bars do not overlap. However, we expect a gap between the best and worst so we must calibrate to judge whether this gap is a real or a selection effect. The probability distribution for the range (maximum minus minimum) of a random sample of size 19 from the same probability distribution can be analyzed by simulation or analytically in some cases. We used simulation and determined that the expected gap is approximately 3.7 standard deviations if the distribution is Gaussian. Therefore, for those cases where the $\mp 2\sigma$ error bars do not overlap, there is at least mild evidence for a real effect. We conclude that there are real differences among the 19 cases. We have also done nonparametric rank tests by comparing the ranks of the probabilities of $10 \times \log_{10}(\frac{\mathbf{R}^2}{\mathbf{R}^2})$ exceeding T for the 19 cases across several partitions. The rankings are consistent enough to suggest that there is a real difference among some of the cases.

Figure (d) is the same as (c) except that it compares the best dynamic case to a static strategy that uses $\overline{\mathbf{R}^2} / \overline{\mathbf{R}^2}_{static}$,

where $\overline{\mathbf{R}^2}_{static}$ is the mean for the entire partition which always covers at least many tens of days. We see from plot (d) that some type of dynamic strategy is much better than a static strategy. The FORTE researchers have always known this, but we are providing a measure of the advantage of using a more frequent ``update-the-mean" strategy.

6 Summary

We have shown that some types of frequent ``update-the-mean" schemes allow the threshold T to be reduced compared to using a static mean. The 19 cases that we evaluated suggest that a large update fraction (UF) and small update interval (UI) are generally preferred. For example, using the previous 10 microsecond window result to predict the current window result performs well. However, if a large threshold such as $T=18$ is used, then neither the dynamic nor the static ``update-the-mean" scheme will alarm on noise very often. Of course it is preferable to reduce T without increasing the false alarm probability. And, we have shown that the current scheme that updates the mean using a update fraction $UF = (50\text{ ms})/(4\text{ s})$ time period every update interval $UI = 4$ seconds should be much better than using a static threshold, although it could probably be improved upon by using a larger UF and a smaller UI.

Once we select an ``update-the-mean" then we expect to select a threshold for each sub-band in a multi-band criterion to locate RF events. Currently, the FORTE master trigger requires that at least five of eight 1 MHz wide sub-bands alarm within a coincidence time τ of the first sub-band trigger. Analytical calculations given in [Burr et. al., 2002b] allow us to evaluate the impact of choosing different thresholds and/or alarm probabilities in each sub-band on the master false-alarm rate. These calculations include the coincidence time τ which is currently 10 microseconds for the hi-band and 160 microseconds for the lo-band. For some coincidence times τ , there will be some ``update-the-mean" rules that require refreshing the background calculation during the coincidence window, which might be undesirable, and would therefore eliminate those rules from consideration.

7 Appendix A: Spectral Analysis Methods

The spectrum of a time series measures the probable amplitude of periodic components (as a function of frequency). It shifts emphasis away from searching for periodicities in a series toward the usually more informative evaluation of the relative amplitudes at all frequencies.

In chapter 7, Bloomfield [2000] refers to methods for estimating ``instantaneous" amplitude or phase as ``complex demodulation." Consider estimating R_t from nonstationary data (let the electric field at the satellite E_t be denoted X_t here), $X_t = R_t \cos(2\pi f_t T + \phi_t) + e_t$, where e_t is noise (or more generally, from data that is a linear combination of many such time-dependent frequencies f_t and amplitudes R_t). The simplest approach is to bin the time series into small time segments and estimate the squared amplitude $(R_t)^2$ for each spectral bin for each time segment. Using a similar approach, [Fitzgerald 2001] estimated the $(R_t)^2$ at each time point but because of smoothing in the frequency domain with a 1 MHz bandwidth, the resulting time series of estimates was then resampled at a lower rate.

Any sequence of n numbers (we assume n is even) has the Fourier series representation $X_t = a_0 + \sum_{p=1}^{n/2-1} \{a_p \cos(2\pi p t/n) + b_p \sin(2\pi p t/n)\}$, where the Fourier coefficients satisfy $a_p(f) = 2/n \sum_{t=0}^{n-1} \{X_t \cos(2\pi p t/n)\}$ and $b_p(f) = 2/n \sum_{t=0}^{n-1} \{X_t \sin(2\pi p t/n)\}$, $a_0 = \bar{x}$, and $a_{n/2} = \sum_{t=1}^{n/2} (-1)^t X_t / n$. It follows (Parseval's theorem) that $\sum_{t=1}^n (X_t - \bar{x})^2 / n = \sum_{p=1}^{n/2-1} \{(R_p)^2 / 2 + (a_{n/2})^2\}$, where $(R_p)^2 = (a_p)^2 + (b_p)^2$ is the squared amplitude of the p^{th} harmonic and a useful form for $p = n/2$ is $X_t = a_0 + \sum_{p=1}^{n/2-1} \{R_p \cos(\omega_p t + \phi_p)\}$ with the phase $\phi_p = \tan^{-1}(-b_p / a_p)$. Parseval's theorem implies that the variance of the n observations can

be decomposed into contributions from each of the harmonics. The plot of $n(R_p)^2/(4\pi)$ versus ω_p is usually called the periodogram, although other definitions have been used.

It is simple to show (using orthogonality of the sin and cosine functions) that if the sequence X_1, X_2, \dots, X_n is independent and identically distributed with the standard normal distribution, then the Fourier coefficients a_p and b_p each have an independent normal distribution with mean zero and variance $2/n$. It also follows that the estimated squared amplitude (R^2) has a $(\chi_2)^2$ distribution, with the scaling factor $\text{sqrt}(2/n)$ (page 90, Bloomfield). We usually plot the estimated R^2 in decibels ($10 \times \log_{10} (R^2)$), and the scaling factor does not impact the range in dB units.

The $(\chi_2)^2$ distribution is commonly called the Rayleigh distribution. [Fitzgerald 2001] investigated the distribution of estimated R^2 using LAPP-generated (Los Alamos Portable Pulser) records and concluded that the Nakagami-Rice distribution provided a better fit than the Rayleigh. The explanation is that FORTE noise is better described by a random Gaussian process superimposed on narrow band transmissions, which is the classic motivation for the Nakagami-Rice distribution. Because the $(\chi_2)^2$ distribution is highly variable, the estimated R^2 is highly variable. Much literature has been devoted to spectral analysis, including methods for smoothing the raw R^2 estimates to reduce variability at the expense of introducing some bias. One goal is to reduce the total variation around the true value. In our case, the time series is nonstationary so the ``true'' value of the R^2 varies over time. We have investigated various tapering and smoothing smoothing schemes, but for our purposes here, it is fully adequate to use a simple defensible spectral analysis method for all 13 geographic regions. All of our presented results use a simple Gaussian-shaped 1 MHz wide smoother. Using simulated data, we ensured that sub-bands separated by 1 MHz or more are uncorrelated when the true input is stationary and that a known signal amplitude at known frequency is recovered exactly (this is not true under various smoothing rules due to leakage).

We estimated R^2 at each center frequency using the fast Fourier transform with 1 MHz wide Gaussian smoothing in Splus [1999]. We then coded those same smoothed cosine and sin transforms in Perl. Because our Splus implementation was too slow for this amount of data, we confirmed that the Perl and Splus implementations gave the same results for a few test cases, and then used Perl for the large-scale problem.

8 Appendix B: Data Description

Data saved for each 10 microsecond window: 57 fields.

- [1] TimeInterval: $(10^{-5}, 4 \times 10^{-4}, 10^{-2}, 10^{-1}, 1, 10)$
- [2] FracTime: Fraction of Time Interval to compute mean: $(0.001, 0.01, 0.1, 1)$
- [3] NoWindowsUsedToComputeMean: Number of windows used to compute the mean
- [4] MeanEndFrame: The frame of the last window used to compute the mean
- [5] StartEvalFrame: The frame of the first window used to begin evaluation

[6-55] 50Values: $10 \times \log_{10} (\mathbf{R}^2 / \overline{\mathbf{R}}^2)$ in a 1 MHz wide sub-band for each of 50 center frequencies (we reported on 44 of these 50) for windows having start times that lie within the appropriate time window as defined by TimeInterval and Fractime. Here, \mathbf{R}^2 is the smoothed estimate of squared amplitude at the center frequency and $\overline{\mathbf{R}}^2$ is the average of R^2 across all 10 microsecond windows within the ``calculate mean'' window.

- [56] WindowMean: mean of the window that defined $\overline{\mathbf{R}}^2$.
- [57] UseintMean: mean of the means of the windows that defined the mean.

9 Appendix C: Numerical Summaries of the Noise Survey Results

The total number of windows used was tens of thousands for all cases except case 21. Case 21 rarely satisfied the criterion so we have only a few hundred or thousands for this case. The smaller sample size for case 21 is reflected in a larger standard deviation across CV partitions of estimated quantiles or fractions exceeding thresholds (relative to what the standard deviation would have been with a larger sample size for each CV partition). For the CONUS and South Atlantic regions, we had no windows for case 21. Because it was simpler to assume that we always had 19 cases with data, we substituted case 22 data for case 21 data, but do then ignore the case 21 summaries because they are not available for the CONUS and S Atlantic regions. Note in figures (e) and (f) of regions 4 (CONUS) and 10 (S Atlantic) that the case 21 result is the same as the case 22 result because of this substitution.

Tabular summary data for each case for each geographic region for the lo and hi band for each of the 44 frequencies are listed here.

For the Africa region Tables 1.1 through 1.19 list the mean statistics by update case listed in [Table II](#) for the lo-band center frequencies and for 6 upper quantiles:

[Table 1.1](#), [Table 1.2](#), [Table 1.3](#), [Table 1.4](#), [Table 1.5](#), [Table 1.6](#), [Table 1.7](#), [Table 1.8](#), [Table 1.9](#), [Table 1.10](#), [Table 1.11](#), [Table 1.12](#), [Table 1.13](#), [Table 1.14](#), [Table 1.15](#), [Table 1.16](#), [Table 1.17](#), [Table 1.18](#), [Table 1.19](#), while Tables 1.20 through 1.38 list the standard deviation statistics by update case for the lo-band center frequencies and the 6 upper quantiles:

[Table 1.20](#), [Table 1.21](#), [Table 1.22](#), [Table 1.23](#), [Table 1.24](#), [Table 1.25](#), [Table 1.26](#), [Table 1.27](#), [Table 1.28](#), [Table 1.29](#), [Table 1.30](#), [Table 1.31](#), [Table 1.32](#), [Table 1.33](#), [Table 1.34](#), [Table 1.35](#), [Table 1.36](#), [Table 1.37](#), [Table 1.38](#).

Tables 1.39 through 1.57 list the mean statistics by update case for the hi-band center frequencies and Tables 1.58 through 1.76 list the standard deviation statistics by update case for the hi-band center frequencies, all for the 6 upper quantiles.

[Table 1.39](#), [Table 1.40](#), [Table 1.41](#), [Table 1.42](#), [Table 1.43](#), [Table 1.44](#), [Table 1.45](#), [Table 1.46](#), [Table 1.47](#), [Table 1.48](#), [Table 1.49](#), [Table 1.50](#), [Table 1.51](#), [Table 1.52](#), [Table 1.53](#), [Table 1.54](#), [Table 1.55](#), [Table 1.56](#), [Table 1.57](#), [Table 1.58](#), [Table 1.59](#), [Table 1.60](#), [Table 1.61](#), [Table 1.62](#), [Table 1.63](#), [Table 1.64](#), [Table 1.65](#), [Table 1.66](#), [Table 1.67](#), [Table 1.68](#), [Table 1.69](#), [Table 1.70](#), [Table 1.71](#), [Table 1.72](#), [Table 1.73](#), [Table 1.74](#), [Table 1.75](#), [Table 1.76](#).

Similarly Tables 1.77 through 1.95 list the mean statistics by update case for the lo-band center frequencies and for the 100 quantiles evenly spaced between 0.9 and 1.0:

[Table 1.77](#), [Table 1.78](#), [Table 1.79](#), [Table 1.80](#), [Table 1.81](#), [Table 1.82](#), [Table 1.83](#), [Table 1.84](#), [Table 1.85](#), [Table 1.86](#), [Table 1.87](#), [Table 1.88](#), [Table 1.89](#), [Table 1.90](#), [Table 1.91](#), [Table 1.92](#), [Table 1.93](#), [Table 1.94](#), [Table 1.95](#), and Tables 1.96 through 1.114 list the standard deviation statistics by update case for the lo-band for the same 100 quantiles:

[Table 1.96](#), [Table 1.97](#), [Table 1.98](#), [Table 1.99](#), [Table 1.100](#), [Table 1.101](#), [Table 1.102](#), [Table 1.103](#), [Table 1.104](#), [Table 1.105](#), [Table 1.106](#), [Table 1.107](#), [Table 1.108](#), [Table 1.109](#), [Table 1.110](#), [Table 1.111](#), [Table 1.112](#), [Table 1.113](#), [Table 1.114](#), and Tables 1.115 through 1.133 list the standard deviation statistics in db by update case for the lo-band for the same 100 quantiles:

[Table 1.115](#), [Table 1.116](#), [Table 1.117](#), [Table 1.118](#), [Table 1.119](#), [Table 1.120](#), [Table 1.121](#), [Table 1.122](#), [Table 1.123](#), [Table 1.124](#), [Table 1.125](#), [Table 1.126](#), [Table 1.127](#), [Table 1.128](#), [Table 1.129](#), [Table 1.130](#), [Table 1.131](#), [Table 1.132](#), [Table 1.133](#).

Likewise Tables 1.134 through 1.190 list the same information for the hi-band frequencies:

[Table 1.134](#), [Table 1.135](#), [Table 1.136](#), [Table 1.137](#), [Table 1.138](#), [Table 1.139](#), [Table 1.140](#), [Table 1.141](#), [Table 1.142](#), [Table 1.143](#), [Table 1.144](#), [Table 1.145](#), [Table 1.146](#), [Table 1.147](#), [Table 1.148](#), [Table 1.149](#), [Table 1.150](#), [Table 1.151](#), [Table 1.152](#), [Table 1.153](#), [Table 1.154](#), [Table 1.155](#), [Table 1.156](#), [Table 1.157](#), [Table 1.158](#), [Table 1.159](#), [Table 1.160](#), [Table 1.161](#), [Table 1.162](#), [Table 1.163](#), [Table 1.164](#), [Table 1.165](#), [Table 1.166](#), [Table 1.167](#), [Table 1.168](#), [Table 1.169](#), [Table 1.170](#), [Table 1.171](#), [Table 1.172](#), [Table 1.173](#), [Table 1.174](#), [Table 1.175](#), [Table 1.176](#), [Table 1.177](#), [Table 1.178](#), [Table 1.179](#), [Table 1.180](#), [Table 1.181](#), [Table 1.182](#), [Table 1.183](#), [Table 1.184](#), [Table 1.185](#), [Table 1.186](#), [Table 1.187](#), [Table 1.188](#), [Table 1.189](#), [Table 1.190](#).

[Table 1.191](#) lists the best grand mean values over each of the 19 cases in Table II for each of the lo-band frequencies, while [Table 1.192](#) lists the best standard deviation values over each of the 19 Table II cases for each lo-band frequency and [Table 1.193](#) lists the best standard deviation values in db over each of the 19 Table II cases for each lo-band frequency. For the hi-band frequencies [Table 1.194](#), [Table 1.195](#) and [Table 1.196](#) list the same information.

SW Pacific: [Table 13.1](#), [Table 13.2](#), [Table 13.3](#), [Table 13.4](#), [Table 13.5](#), [Table 13.6](#), [Table 13.7](#), [Table 13.8](#), [Table 13.9](#), [Table 13.10](#), [Table 13.11](#), [Table 13.12](#), [Table 13.13](#), [Table 13.14](#), [Table 13.15](#), [Table 13.16](#), [Table 13.17](#), [Table 13.18](#), [Table 13.19](#), [Table 13.20](#), [Table 13.21](#), [Table 13.22](#), [Table 13.23](#), [Table 13.24](#), [Table 13.25](#), [Table 13.26](#), [Table 13.27](#), [Table 13.28](#), [Table 13.29](#), [Table 13.30](#), [Table 13.31](#), [Table 13.32](#), [Table 13.33](#), [Table 13.34](#), [Table 13.35](#), [Table 13.36](#), [Table 13.37](#), [Table 13.38](#), [Table 13.39](#), [Table 13.40](#), [Table 13.41](#), [Table 13.42](#), [Table 13.43](#), [Table 13.44](#), [Table 13.45](#), [Table 13.46](#), [Table 13.47](#), [Table 13.48](#), [Table 13.49](#), [Table 13.50](#), [Table 13.51](#), [Table 13.52](#), [Table 13.53](#), [Table 13.54](#), [Table 13.55](#), [Table 13.56](#), [Table 13.57](#), [Table 13.58](#), [Table 13.59](#), [Table 13.60](#), [Table 13.61](#), [Table 13.62](#), [Table 13.63](#), [Table 13.64](#), [Table 13.65](#), [Table 13.66](#), [Table 13.67](#), [Table 13.68](#), [Table 13.69](#), [Table 13.70](#), [Table 13.71](#), [Table 13.72](#), [Table 13.73](#), [Table 13.74](#), [Table 13.75](#), [Table 13.76](#), [Table 13.77](#), [Table 13.78](#), [Table 13.79](#), [Table 13.80](#), [Table 13.81](#), [Table 13.82](#), [Table 13.83](#), [Table 13.84](#), [Table 13.85](#), [Table 13.86](#), [Table 13.87](#), [Table 13.88](#), [Table 13.89](#), [Table 13.90](#), [Table 13.91](#), [Table 13.92](#), [Table 13.93](#), [Table 13.94](#), [Table 13.95](#), [Table 13.96](#), [Table 13.97](#), [Table 13.98](#), [Table 13.99](#), [Table 13.100](#), [Table 13.101](#), [Table 13.102](#), [Table 13.103](#), [Table 13.104](#), [Table 13.105](#), [Table 13.106](#), [Table 13.107](#), [Table 13.108](#), [Table 13.109](#), [Table 13.110](#), [Table 13.111](#), [Table 13.112](#), [Table 13.113](#), [Table 13.114](#), [Table 13.115](#), [Table 13.116](#), [Table 13.117](#), [Table 13.118](#), [Table 13.119](#), [Table 13.120](#), [Table 13.121](#), [Table 13.122](#), [Table 13.123](#), [Table 13.124](#), [Table 13.125](#), [Table 13.126](#), [Table 13.127](#), [Table 13.128](#), [Table 13.129](#), [Table 13.130](#), [Table 13.131](#), [Table 13.132](#), [Table 13.133](#), [Table 13.134](#), [Table 13.135](#), [Table 13.136](#), [Table 13.137](#), [Table 13.138](#), [Table 13.139](#), [Table 13.140](#), [Table 13.141](#), [Table 13.142](#), [Table 13.143](#), [Table 13.144](#), [Table 13.145](#), [Table 13.146](#), [Table 13.147](#), [Table 13.148](#), [Table 13.149](#), [Table 13.150](#), [Table 13.151](#), [Table 13.152](#), [Table 13.153](#), [Table 13.154](#), [Table 13.155](#), [Table 13.156](#), [Table 13.157](#), [Table 13.158](#), [Table 13.159](#), [Table 13.160](#), [Table 13.161](#), [Table 13.162](#), [Table 13.163](#), [Table 13.164](#), [Table 13.165](#), [Table 13.166](#), [Table 13.167](#), [Table 13.168](#), [Table 13.169](#), [Table 13.170](#), [Table 13.171](#), [Table 13.172](#), [Table 13.173](#), [Table 13.174](#), [Table 13.175](#), [Table 13.176](#), [Table 13.177](#), [Table 13.178](#), [Table 13.179](#), [Table 13.180](#), [Table 13.181](#), [Table 13.182](#), [Table 13.183](#), [Table 13.184](#), [Table 13.185](#), [Table 13.186](#), [Table 13.187](#), [Table 13.188](#), [Table 13.189](#), [Table 13.190](#), [Table 13.191](#), [Table 13.192](#), [Table 13.193](#), [Table 13.194](#), [Table 13.195](#) and [Table 13.196](#).

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